Science & Global Security, 1999, Volume 8:2, pp. 217-259
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Response to *Science & Global Security* Article "Technical Debate over Patriot Performance in the Gulf War" by Jeremiah Sullivan et al.

Robert M. Stein[a], John P. Kantelis[b], and Peter D. Zimmerman[c]

(This comment has not been fully peer reviewed in the usual manner of the journal.)

INTRODUCTION

In 1993, the Panel on Public Affairs of the American Physical Society established an ad hoc panel, chaired by Jeremiah Sullivan, to look into the then two and one half year old debate about Patriot performance in the Gulf War. In May 1993, Sullivan and his panel (the panel) held a one day meeting at which some of those who had been involved in the debate were invited to discuss their views. Now, more than six years later and nearly nine years after the war, the panel has published a report (the Sullivan report) on their examination.[1] Although we are in almost complete agreement with the high level "Lessons Learned" that conclude the Sullivan report, we disagree with many of its principal findings and detailed assessments.

a Robert M. Stein, Vice President Raytheon Company, Advanced Systems
b John Kantelis, Senior Principal Systems Engineer, Raytheon Systems Company
c Peter D. Zimmerman, U.S. Department of State (At the time this article was written, he was principal, Zimmerman Associates)

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Our response will focus on four specific issues:

Success Criteria

We argue that Postol and Lewis (P&L) have established a methodology and criteria for "failure" that all but guarantee Patriot could never achieve, according to their definition, a "successful" intercept in the Gulf War. The panel, however, in focusing so heavily on the details, appears to have missed this overarching issue. We show that only one of P&L's failure criteria is unambiguously so (the presence of extensive ground damage) and accounts for only 28% (8 out of 29 "events") of P&L's "failures." Of the remaining 72% (21 events), we show that all but four (17 events) derive from failure criteria that have little, if any, definitive scientific basis.[2]

End-Game Video Analysis

This area has been the primary focus of the P&L methodology and controversy -- the gross determination of lethal and non-lethal end-game miss distances from examination of uncalibrated, slow speed press video tapes taken during the Gulf War. Yet, despite all of the years of argument and discussion, only 14% (the four events in the "all but four" mentioned in "Success Criteria" above) of P&L's "failures" derive from this analysis. The question here, even for these four events, is whether or not the P&L methodology holds up to detailed scrutiny and yields *unambiguous* results. We will show that the Postol and Lewis end game video analysis methodology does not yield unambiguous results and that a determination of failure using this methodology cannot be relied upon. Our finding in this regard differs considerably from that of the panel.[3]

Errors and Omissions

The Sullivan report contains a number of errors and several omissions of important facts. Many of these errors affect the conclusions of their analyses. We correct some of the more important errors, fill in the missing facts and highlight their significance.

Significance of the Patriot Debate and the Usefulness of P&L's Video Analysis

All of the above aside, we believe that there is virtually no significance to either the Patriot system or to theater missile defense as a whole left in this protracted debate.[4] Both the Patriot system today (which has undergone two major upgrades since the war) and the evolution of other theater missile defenses, now well underway, are not directly related to any of P&L's analyses or issues, even according to the panel.[5]

In the remainder of this response, we discuss each of these four issues in detail.

POSTOL AND LEWIS' "SUCCESS" CRITERIA VIRTUALLY GUARANTEE 100% "FAILURE"

In essence, P&L demand that four specific criteria have to be satisfied before they are willing to call any Patriot engagement of a Desert Storm Scud "successful." Table 1 in this response reorders the 29 P&L Scud events of the Sullivan report's Table A and Table B into these four criteria. To these four we have added an "other" category, because P&L score two of the 29 events as "failures" based upon "other" factors, even though these two events survive each of the specific four criteria.

1. Ground Damage

The engaged Scud cannot have caused any extensive damage on the ground. This is identical to one of the criteria the Army used in their evaluation and with which we agree. Clearly, a Scud which caused significant damage on the ground was not successfully intercepted. Eight of P&L's 29 "events" (28%) are scored as "failures" based upon this criterion and do not depend upon any other less compelling "video evidence" analyses.

2. "Clear Misses"

Even in the absence of reported ground damage, the Scud or, if broken up, its detached warhead (in effect a re-entry vehicle or "RV"), assumed by both P&L and the panel to be the falling dot of light in the videos, must be enveloped within at least one Patriot fireball (called a "fireball overlap") in the video frame that contains the first occurrence of that fireball. Any intercept which does not result in a fireball overlap is deemed to be a "clear miss."[6] This is the part of P&L's analysis in which most work appears to have been done and for which the most compelling technically defensible arguments have been presented. Four of P&L's 29 "events" (14%) are classified as failures based on this criterion not being met.[7]

Table 1: P&L's 29 Scud Events Ordered Into the Five Principal "Failure" Criteria

"Failure" Criterion	# of Events Scored with This Criterion	% of All Events	Most Compelling Postol/Lewis Reason for "Failure"	Events in This Category	Comments
1 Ground Damage	8	28%	Extensive Ground Damage Reported (EGDR)	A1, A3, A7, A9, A11, B1, B11, B12	Similar Criterion to One of Those Used in Army Assessment
2 "Clear Misses"	4	14%	No EGDR, but All Intercepts Appear as "Clear Misses" (CMs) in P&L Terminology	A2, A10, A12, A13	A1,A3, A7, A9 Also in This Category, but Counted in "Extensive Ground Damage Reported"
3 High Speed Emerg-ing Dots of Light	3	10%	Unchanged Ball of Light/Trajec-tory (UBoLT) Emerges from Patriot Fireball after Intercept	A5, A14, A17	No EGDR, No Evidence that All Intercepts Are "Clear Misses"
4 Flashes of Light on the Ground	12	41%	Ground Flashes (GF) Observed	A6, A8, A15, A16, B2, B3, B4, B5, B6, B7, B8, B9	No EGDR, No Evidence that All Intercepts Are "Clear Misses", No UBoLT

Table 1: P&L's 29 Scud Events Ordered Into the Five Principal "Failure" Criteria

"Failure" Criterion	# of Events Scored with This Criterion	% of All Events	Most Compelling Postol/Lewis Reason for "Failure"	Events in This Category	Comments
Other	2	7%	As Noted	A4, B10	See page 221, "Other"

3. High Speed Emerging Dots of Light

In the absence of reported ground damage and in the event of a fireball overlap, anything (i.e., a dot of light) emerging from the Patriot fireball after it envelopes the RV must be on a different trajectory from the dot of light entering and in some way change its appearance. Three events (10%) are scored as failures based on failing this criterion.

4. Flashes of Light on the Ground

In addition to the three criteria above, no flash of light must appear on the ground after the engagement. Twelve events (41% and the largest population in any category) are scored as failures based on this criterion.[8]

Other

The two remaining events (7%) survive the four criteria above, but even they are scored as failures. One of these events "fails" even though there was no ground damage reported, a "fireball overlap" occurred, the object emerging out of the fireball had experienced a significant change in appearance and no ground flash was seen. The P&L reasons for scoring these events as failures -- an erroneous argument about dudding by Patriot fragments (see our "Significant Errors and Omissions" section) and a lack of publicly available evidence that Patriot disabled the warhead.[9] The other "fails" because P&L conclude, despite a lack of ground damage and lack of video data showing anything but the initial appearance of the Scud and two subsequent Patriot launches, that the intercept failed because the Patriots were launched too late. How they can make this determination without definitive knowledge of the Scud trajectory and impact point relative to the Patriot launcher location, the altitude of the initial glimpses of the Scud and the specific drag characteristics of that particular Scud is at best unclear. In fairness to the panel, they treat this as a "special case" (page 20) and reserve judgement on "the quality of [P&L's] evidence."

We have listed these P&L criteria in what we believe is decreasing supportability. In particular, criteria three, four and "other" are far less credible and supportable than one and two. Moreover, in combination, three, four and "other" are not easily satisfied unless a Patriot intercept literally disintegrates a Scud. No one, not even the most ardent Patriot supporters, ever argued that Patriot disintegrated Scuds during Desert Storm. De facto, *playing by the P&L rules, it was virtually impossible for Patriot ever to score a success*.What is surprising to us is that the panel never even addresses the common sense implication of the entire chain of P&L's success criteria, i.e., the virtual inability of any event to pass all of their tests.

58% of P&L's Patriot "failures" stem from criteria three, four or "other." The use of the "other" category is unsupportable on its face since all successes could still be deemed to fall into that box. Criteria three and four are supportable only if a Patriot intercept failure is the only plausible interpretation for an unchanged emerging ball of light or a ground flash. A failure is not the only explanation, for the reasons we set forth below.

High Speed Emerging Dots of Light

Does the existence of a fast-moving dot of light with a relatively unchanged trajectory emerging from the Patriot fireball, by itself, really signify an intercept failure?[10] We believe it does not. It only signifies that whatever caused a physical object to appear as a falling dot of light to appear to the video cameras before the intercept, the same or a similar mechanism still existed in some form after the intercept, i.e., *the Scud was not disintegrated*, and the momentum transfer from the Patriot to the Scud or the change in the Scud's aerodynamic characteristics was not sufficient to knock the Scud off course significantly. An unchanged trajectory would, in fact, be the case if the Scud were hit with a lethal but small number of fragments. Whether or not the ball of light was the RV; whether or not the Scud warhead remained functional; whether or not the warhead shell had been perforated, making a high order explosion impossible; and whether or not the RV's fuze, batteries, cabling or safety and arm device had been destroyed by fragment penetrations cannot be determined simply from the presence of a fast moving small dot of light.

In all of the years of trying by P&L, and in the six years that the panel worked on their report, neither P&L nor the panel has ever been able to explain definitively the cause or source of the visible dot of light.[11] To base a conclusion of success or failure solely on the qualitative appearance or characteristics of a phenomenon whose basic existence cannot even be explained seems at best questionable. Yet that is what P&L have done on many of these assessments; surprisingly, the panel appears to accept it.

Flashes of Light on the Ground

If a fast moving emerging dot of light (criterion three) is not conclusive evidence of failure, what about flashes of light on the ground (criterion four)? These form the basis for almost half of P&L's claimed failures. Such flashes signify little beyond the fact that a significant energy release took place when something hit the ground. Whether that energy release came from a chemical source such as a warhead detonation or from a fuel/air explosion from an unspent fuel tank, from the conversion of kinetic energy to heat caused by a rapidly falling body hitting the ground or from a combination of the two cannot be determined from the types of video that are available.

The panel devotes considerable discussion to the phenomenology of ground flashes. Unfortunately, they do so not from the broad perspective of establishing the range of alternative explanations for the source of the ground flashes, but from a much narrower perspective -- that of determining whether the flashes could have been made by a warhead detonation.[12] After much discussion about the complications involved, the lack of detailed knowledge about the conditions inside a Scud warhead, the limitations of the slow frame rate of the cameras, the inadequate dynamic range of a commercial video camera video detection array, the lack of calibration in the cameras, the color distortion produced by the camera automatic gain control, the distortion created by atmospheric effects, etc., they conclude that the ground flashes seen in the videos are consistent "with the optical emissions expected from the post detonation phase of Tritonal. . ." All other possible explanations are dismissed.[13]

In their entire lengthy discussion of ground flashes, the panel never even mentions the likelihood of flashes being created simply from the kinetic energy released from the impact of an intact Scud or a heavy fast moving object such as a disabled warhead section that broke off late in flight. In their own table in Appendix B, the panel calculates the energy released from the ground impact of an intact missile with no explosion (2300 million joules) and the chemically released energy from an exploding warhead (1100 million joules). If this exploding warhead was attached to an intact missile, then the combined energy release would approach the sum of the two energies or 3400 million joules. No evidence is ever presented by the panel that the case of a kinetic-only impact *with no warhead detonation* can be reliably differentiated from the case of approximately 50% lower energy (an explosion from a detached warhead) or about 50% higher energy (an explosion from an attached warhead). Indeed, videos of the kinetic-only impacts from the Army Line of Sight Anti-Tank (LOSAT) missile with much lower kinetic energy conversion than that from a falling Scud look remarkably similar, at least as to flash onset and decay rate, to some recorded ground flashes in the Gulf War.[14] More recently, tests of 7.5 gram two km/sec tungsten cube impacts conducted at a DASA facility in Schrobenhausen, Germany, under a NATO Medium Extended Range Air Defense experimental program, with kinetic energy five orders of magnitude less than non-exploding 600 Km Scuds, also show the same kind of bright characteristic flashes. The simple conclusion is that bright visible flashes do not necessarily connote exploding warheads and therefore cannot be used as a criterion for judging intercept success.

Much of the panel's argument on ground flashes hinges on their belief that nearly all impacting Scuds *exploded* on the ground. This belief stems from the meaning of the word "dud." The panel defines a dud as a Scud that doesn't explode when it hits the ground ("when a Scud warhead reaches the ground it either explodes or it is a dud.")[15] Based upon this definition and the fact that the Army reported recovering only a total of four duds,[16] the panel concludes (incorrectly) that each of the other Scud warheads must have exploded. QED, or so they imply.

The central error in all of this is that the word "dud," which is the key to the panel's logic, means something different to them than it does as used by the Army. The panel defines a dud as any Scud that doesn't explode. The Army classified four Scuds as "duds" because they were intact enough to be confirmed as duds *based upon the recovered debris*. That did not mean that all other Scud warheads exploded when they hit the ground. Indeed, other non-exploding warheads did occur as evidenced by the existence of very small craters at the impact point -- craters not at all consistent in either diameter or depth with those created by high order explosions -- and by the lack of other high-order detonation damage to the surrounding area. In some cases the failure to explode was due to damage the warheads suffered from a successful Patriot intercept. Such events are known to have happened because parts of the Scud armament and guidance sections were recovered with Patriot fragment holes and other pieces of Patriot missiles imbedded in them.[17] It is this "disconnect" in definitions that causes the panel to conclude and then build an argument upon the mistaken argument that only three engaged Scuds failed to explode on the ground.

The panel dismisses alternative ground flash explanations based upon their definitional argument about duds. They build a seemingly self-consistent story that says in essence: (1) since the Army reported only a few duds, there must have been many Scud warhead explosions on the ground; (2) since there were many explosions on the ground, there must have been many ground flashes; (3) since the ground flashes, as recorded on press video tape " . . . are consistent with the optical emissions expected from . . the explosive used in the Scud warheads;" then each video-taped ground flash confirms the explosion of a Scud warhead and therefore, a Patriot failure ("Hence, except for duds, all intact Scud warheads that reached the ground must have exploded on impact, and thus all cases in which the warhead is tracked all the way to the ground contain video imagery of the warhead detonation"). This circular argument has two fundamental flaws. First, as we discussed above, a detonating warhead is clearly not the only plausible cause of a video-recorded ground flashes. Second, the assertion made by the panel that all warheads, except for the duds identified by the Army, exploded on the ground is wrong and results from their misunderstanding of the Army's use of the term "dud."

In summary, 8 of P&L's 29 events (28%) are associated with heavy ground damage and can be accepted as unsuccessful Patriot engagements. 17 additional events (58%)[18] are scored as failures by P&L based upon criteria that are either ambiguous or lack a clear scientific basis, including emerging fast moving dots of lights, ground flashes and the two other events for which the "failure" rationales defy characterization. This leaves only four of the 29 events (14%) to consider further, those in which the primary evidence for failure is a video record of only "clear miss" intercepts in the P&L terminology (our criterion two). Interestingly, in these four engagements[19] with an apparent record of no ground damage and only "clear misses," only two would be in dispute between the P&L interpretation and the Army's assessment.[20] In both cases, hard evidence was found to support an assessment of success -- in one case recovered Scud debris with Patriot fragment holes and in the other, recovered debris imbedded with Patriot warhead and guidance parts. This leaves one small piece of the puzzle yet to explain -- how could such hard evidence for success exist for these two engagements, when only "clear misses" appear in the videos. We could simply dismiss these two cases as being too few to bother with,[21] or we could try to explain why, on occasion, even large video-apparent misses can actually be successful intercepts. We consider this question next.

TERMINAL ENCOUNTER VIDEO EVIDENCE AND "CLEAR MISSES"

Far more compelling than emerging balls of light or ground flashes, at least upon casual examination, is the P&L analysis of commercial video imagery at the time the Patriot missile detonates its warhead. From this fraction of a second of video imagery, P&L conclude via geometrical arguments that some intercepts (the four[22] in our "criterion two") were failures primarily because of the apparent separation between the Scud and the Patriot fireball on the video screen at approximately[23] the time of detonation. In this section we will show that in their oversimplification of the engagement geometry, P&L have created, and the panel has endorsed, a video imagery evaluation methodology that has the potential, on occasion, to classify a successful intercept incorrectly as a "clear miss."

In their analysis, P&L present a simplified model of the Patriot/Scud intercept geometry. First, they fail to take into account the angle of attack[24] of the Patriot during the final stages of the end-game. Because Patriot's "optimal guidance" algorithms determine that the remaining time to go is approaching zero and a finite miss distance remains, the guidance system will tend to call for maximum lateral acceleration at the end (and therefore, depending upon altitude and velocity, the autopilot will call for high angle of attack). This changes the relation of fuze cone angle and warhead spray angle relative to the Patriot missile velocity vector and may actually help or hurt end-game lethality, depending upon the direction of angle of attack relative to the rest of the end-game geometry. This effect is not accounted for in the P&L analysis. Second, P&L model the intercept geometry as two-dimensional with anti-parallel trajectories, when, in fact, the geometry is generally three-dimensional with trajectories that cross, sometimes at substantial angles. We will demonstrate that when these simplification errors are corrected, an entirely different account of the video images can result, one in which P&L's "clear misses" can actually be valid kills.

The panel's analysis of the P&L end game geometry uses several length measures to describe the relative positions of the Scud and Patriot. Among these are "miss distance" and a parameter the panel calls "MDT" -- the distance separating the Patriot and Scud when the warhead is detonated. The panel appears to treat these interchangeably,[25] when actually, these distances differ in important ways.

It is common practice in the missile guidance community to use the term "miss distance" to describe the separation distance between the target and the interceptor when they would be at their points of closest approach. We say "would be" because the warhead must detonate ahead of this point, a fact noted by P&L,[26] causing the closest approach to "occur" only after the interceptor has destroyed itself. Guidance, fuzing, missile control and warhead lethality are based on this definition.

Quite different from miss distance is the separation distance when the warhead detonates (MDT in the panel's terminology). This parameter is merely the length of the straight line connecting the Patriot warhead and Scud warhead when the Patriot warhead is detonated. By definition, it is always greater, sometimes much greater, than the miss distance. Consideration of the final moments of an intercept reveals why.

In a typical (non-direct hit) intercept, the Scud and Patriot will pass each other laterally at some distance. Since the warhead fragments are not ejected at infinite velocity, it takes a period of time for them to move into the path of the approaching Scud. It is allowance for this period of time (the primary function of the fuze) that requires the warhead to be detonated prior to closest approach. Depending on the particulars of the engagement (particularly true miss distance and closing velocity) and the angle of attack of the Patriot, this separation distance, for the high-speed encounters between Patriot and Desert Storm Scuds, can be larger than the miss distance by as much as a factor of two. Except for the smallest of miss distances, MDT, as defined by P&L and the panel, has to be significantly greater than the miss distance, since anything less would mean that the fragments are released too late and would simply pass behind the intended target.

A second issue lies in the panel's acceptance of P&L's assumption or oversimplification that the Patriot and Scud trajectories are anti-parallel, i.e., their velocity vectors are parallel but in opposite directions. This is never precisely achieved in general and was particularly not true for many intercepts during the Gulf War. Although, under ideal circumstances, the Patriot missile midcourse guidance algorithm attempts to achieve a near anti-parallel course,[27] a combination of two factors hampered the ability of the system to accomplish that in the Gulf War. First, many intercepts occurred at relatively low altitudes because of the high speed of the target, the desire to "reach out" and achieve a more extended area defense than Patriot's design objective and, in some cases, the effects of manual operation and its attendant increase in system reaction time. Second, sometimes the Patriot launcher was well off to the side of the vertical plane containing the Scud trajectory, another consequence of extending the area defense capability of the system. Together, these two factors reduced the combination of time, maneuver space, lateral acceleration and turning rate available for the Patriot missile to swing around into position and establish an anti-parallel trajectory. This resulted in velocity

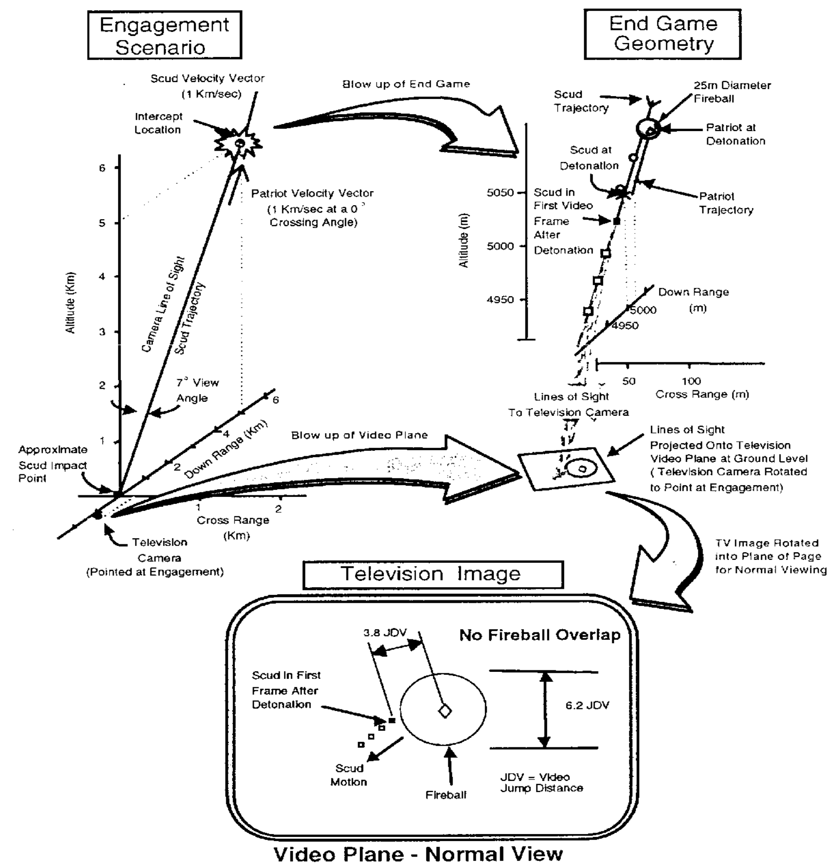

Figure 1a: Geometric Basis of Video Image of an Unsuccessful Patriot Intercept.

vectors that were up to 30 degrees off the anti-parallel – a minor effect from a lethality point of view, but sometimes of major significance in the understanding and interpretation of the P&L videos.

In order to evaluate the impact of this more complete definition of the intercept geometry on the interpretation of P&L's video imagery, we will introduce the two geometric factors just discussed, non-zero crossing angle and MDT larger than miss distance, into the P&L analysis. That will render the P&L "failure" criterion of an "unambiguous" video apparent miss (our number two) as flawed and not, as they claim, unambiguous. To illustrate the poten-

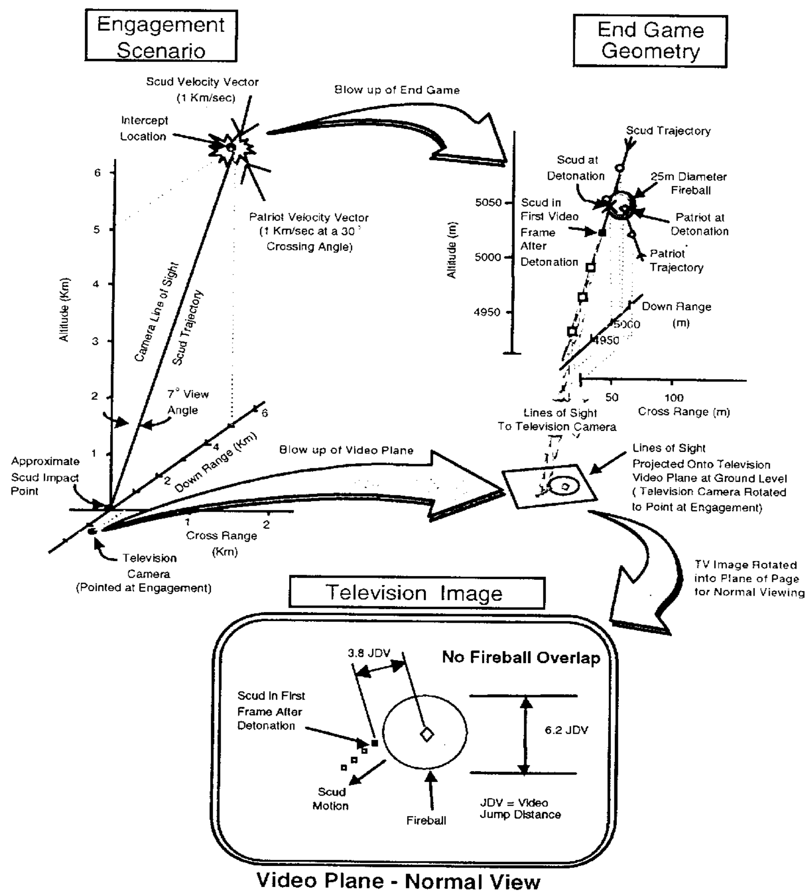

Figure 1b: A Successful Patriot Intercept Can Appear Unsuccessful on Video Under Certain Conditions.

tial for ambiguity, we will show an example of a successful intercept which, if analyzed using P&L's methodology, would be incorrectly scored as a clear miss.[28]

We consider the scenario shown in Figures 1a and b. Within this scenario two cases are depicted -- an unsuccessful intercept in part a and a successful intercept[29] in part b. When viewed side by side as two dimensional video images (the "Video Plane-Normal View" in Figures 1a and 1b and the TV screen simulated picture in Figure 2), however, they are indistinguishable, with both appearing as "clear misses" in P&L's terminology. The scenario is defined as follows. In both cases we model a low altitude intercept in which the descending Scud has slowed to 1 km/sec[30], the Patriot missile is climbing towards the Scud at a speed of 1 km/sec and a spherical fireball with a true diameter of 25 m is generated when the Patriot warhead detonates.[31] In the successful intercept case, the Patriot approaches at a 30 degree crossing angle with a miss distance of 10 m.[32] In the unsuccessful case the Patriot missile approaches on an anti-parallel course (the case generally modeled by P&L) with a true miss distance much greater than 10 m.[33] In both cases a viewing angle of 7 degrees is modeled, with the camera located on the ground –1.4 Km downrange and 170 meters crossrange from the impact point.

On the left side of each part of Figure 1, an overview of the three-dimensional engagement is portrayed showing the relative positions of the intercept, the projected impact point of the Scud and the viewing position of the television camera. In the upper right of each figure a close up of the intercept is provided, in which, using the panel's symbology, the positions of the Scud, at the times they are captured in the video frames, are shown as circles before detonation and squares after detonation. The Scud's video location in the frame immediately after detonation is shown by the solid square. The location of the Scud at the time of warhead detonation (which generally occurs between video frames) is indicated by the X on the Scud's trajectory line. The positions of Scud images and the Patriot fireball, as they would appear captured on video, are obtained by projecting the Scud and Patriot locations down onto the flat video plane oriented at the designated viewing angle and rotated in three dimensions to point directly at the engagement. Finally, the flat video plane is rotated into the plane of the page to appear as it would on a television screen.[34] The corresponding two video sequences of images, as they would appear on television before representative panning and jitter were removed, are illustrated in Figure 2 for both the unsuccessful and successful intercepts described above.

The most striking feature of the video images is that both the clear miss and the successful intercept appear exactly the same; they cannot be distinguished. In these two cases, with video evidence from only a single camera, distinguishing the unsuccessful from the successful intercepts would not be possible. Further, the fireballs do not overlap the Scud and appear behind and off to the side, for both the successful and the unsuccessful intercept. For the successful intercept, this trailing fireball is, of course, just an illusion created by the non-parallel trajectories and the particular viewing angle. But most important, not only are the images from the successful and unsuccessful intercepts exactly the same with the non-overlapping fireball trailing the Scud, but

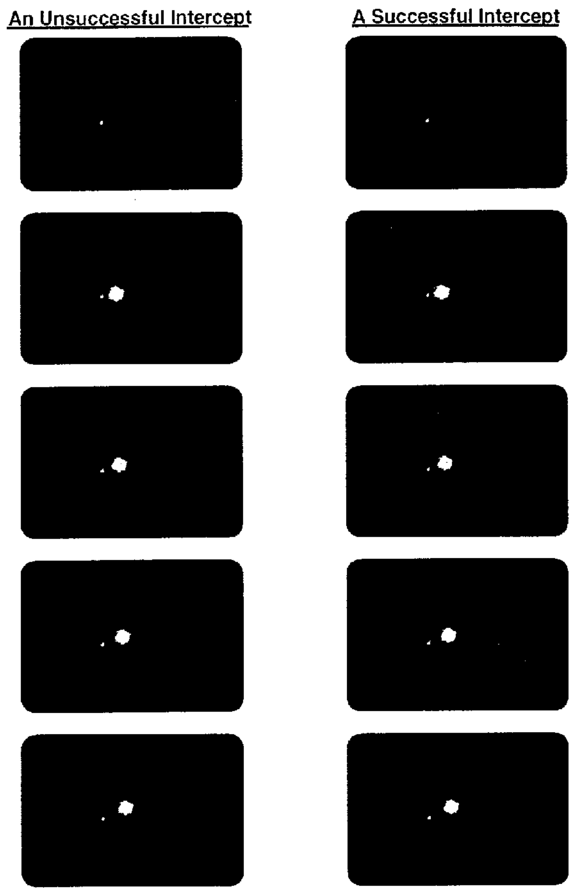

Figure 2: Simulated TV Picture Sequences.

the apparent miss for both cases is 3.8 video jump units; *an MDPL in the upper part of the bimodal distribution which the panel considers a clear miss*.[35]

Finally, it is interesting to reevaluate the video-apparent diameter of the Patriot fireball in view of this scenario. According to the panel, the apparent diameter of the video fireballs, *using P&L's measuring technique and assumed parameters*, was 50 to 400 m, although they admit that these sizes are inexplicably large.[36] We share their lack of understanding of the too-large fireball diameters and are accordingly wary, in fact more wary than the panel, of using what may be a camera artifact or imperfect measuring technique, for any analytical purpose, including *asserting anything in absolute terms about situations in which fireball overlaps "must occur."* We note below, however, how the true fireball diameter could appear completely consistent with the larger video-apparent values reported by the panel, using only a slightly different set of assumptions in their model.

The method used by P&L and the panel to estimate fireball diameters from the video images used the video jump distance of the Scud along with assumptions about its velocity and the camera viewing angle. They use the simple relationship:

$$\text{Fireball Diameter} = \#JDV * V_{scud} * \sin(\alpha) / 30 \qquad (1)$$

where #JDV is the apparent diameter of the fireball measured in video jump units, V_{scud} is the speed of the Scud, and α is the viewing angle, which creates a dilution of geometry and has to be corrected out. This estimate of diameter is obviously only as accurate as the estimates of V_{scud} and α (obviously, if we evaluate Equation 1 using the measured #JDV in our model case and the true values of V_{scud} and α (i.e., 6.2, 1 km/sec and 7^o), we recover the correct fireball diameter of 25 m. It is never quite clear when P&L use "typical" values, when they use individual case estimates or how accurate these estimates are when they do use them. However, both the panel and P&L have referred previously to typical values of V_{scud} in the range of 2.0 to 2.2 km/sec (upper end of the Patriot battle space and a stable extended-range Scud warhead section flying in a non-coning or non-spiraling condition) and α values in the range of 6 to 37 degrees.[37] The fireball diameter measured from the screen in our example case is about 6.2 video jump units. If we now used P&L's mid-values for V_{scud} and α, i.e., 2.1 km/sec and 21.5 degrees, then Equation 1 would lead us to believe we were seeing a fireball diameter of 159 m, when what was really on the screen was a true fireball diameter of 25m.[38] Further, if we evaluate Equation 1 at the limits of P&L's angle and velocity ranges, we obtain an estimated range of fireball diameters from 43 m to 274 m; all with significant error (up to a factor of more than ten times the true *observed*, let alone the true actual, diameter), but consistent with the panel's reported range of observed diameters.

We do not claim that all of the eight events observed as having only "clear misses" in the P&L end-game videos were actually successful intercepts (see our note 19). Certainly the four that were associated with extensive ground damage were not. But two of the remaining four, based upon quite compelling evidence as discussed previously, appear to have been successful and our analysis clearly explains how oversimplification or modest errors in the assumed intercept geometry can create this apparent discrepancy. Other issues may also still exist because of the fundamental limitations of P&L's data medium. One thing is clear, however. P&L's and the panel's assertion that a Patriot fireball that appears more than three video jump units distant from the Scud, i.e., in the upper portion of the claimed bimodal miss distance distribution, cannot have led to a successful intercept is untenable.

ERRORS AND OMISSIONS IN THE SULLIVAN REPORT

In this section we correct some of the more important errors in the report and fill in some information that, although left out of the Sullivan report, is necessary to obtain a more complete and balanced understanding of the debate concerning Patriot performance in 1991.

Recording Devices

The report states on page three that "many air defense radars have built-in recording systems as standard equipment." This is not correct. Until quite recently, recording devices with sufficient mass storage capability to capture long records of high bandwidth data, in packages small enough to fit into ground-mobile control stations, with the ruggedness to survive movement across the battlefield did not exist. Such devices are now available and Patriot is the first operational ground-based tactical air defense system to install them. In spite of this lack during the Gulf War, Patriot operators did manage to capture a significant amount of data manually.[39]

Patriot System Description

The range of the Patriot missile, as stated by the panel on page four, is grossly in error. Its true range is many times that stated in the report. The claim in note 5 that "[Patriot] had a limited capability to perform high-precision calculations" is misleading.[40] The description of the self contained fusing radar, its operation, and the Patriot guidance scheme on page four is in error and is more descriptive of command guidance than radar homing guidance.[41]

Al-Hussein Missile Breakup

It is incorrect to conclude that Iraqi-modified Scuds, as the report states on page five, "typically broke up during reentry." There was no such thing as "typical." Some Scuds broke up on reentry, others broke up during ascent and some did not break up at all, as evidenced by the data collected in the track amp tabs, PC recordings and video recordings mentioned in our note 39. P&L's analytical use of "average" or "typical" target velocities at low altitude[42] are inconsistent with these erratic and widely varying breakup phenomena. In addition, because these warheads were not designed to separate from the missile body, one would never expect to have seen a "clean," high beta reentry.

Casualties and Ground Damage in Israel

The report's recap of this early debate is incomplete. Although the panel presents Postol's summary position (page 7 and note 16), they offer no description of the rebuttal position, other than to say there was one by Stein (note 17) as well as some other "criticisms." Some of these rebuttals, however, were far more than just mere criticisms. Using the same source data as Postol, but applying the correct interpretation of ground damage and the proper arithmetic, one arrives at exactly the opposite conclusion from that of Postol, namely, that all but superficial ground damage in Israel actually *decreased after the introduction of Patriot*. Depending upon which statistics are used, the decrease in casualties and destroyed buildings was between 33 percent and 57 percent, not inconsistent with the Army's score in Israel of achieving a success rate of "over 40%."[43]

The report also fails to mention that Postol himself eventually backed away from his earlier claims, as was noticed and remarked upon by others in academia who followed this debate.[44] The panel refers to the later study of Fetter, Lewis and Gronlund (originally released as a Working Paper from Postol's Defense and Arms Control Study Program (DACS) Program) and claim that their results "supported the findings of the earlier Postol study." However, that is not quite the case. The Postol studies, as noted by the panel, claimed that the damage statistics demonstrated the lack of success of Patriot. The Fetter paper, on the other hand, concludes something quite different – that the ground damage statistics in Israel don't prove that Patriot worked ("The available evidence does not support claims that the Patriot missile defence system significantly reduced casualties in Israel").[45] This is a much diminished claim from that of Postol's. The panel also fails to inform their readers that the Fetter et al. study itself became the subject of critical analysis and that its findings were hotly disputed by others in academia. Robin Ranger, a Research Associate at the Center for Defence and International

Security Studies at Lancaster University in the UK wrote, ". . . the British experience [with the V2 missile] shows that the very low casualties in Israel and Saudi Arabia can be explained only as the result of a combination of active and passive defences . . . analyses attempting to argue that low casualties in Israel were the result of factors other than successful intercepts by Patriot ATBM systems are invalid. . ."[46]

Army Studies

The panel discusses the analyses of ground damage used in the Army's assessment and repeats the view held by most observers that the Israeli data base was constructed in a more methodical and complete manner than that in Saudi Arabia. Having introduced this, the panel then states that they do "not know whether the Israeli data were used in the Army studies." In fact, as publicly stated in the April 1992 Congressional Hearing[47] and at the May 1993 ad hoc panel meeting, the Israeli data and subsequent Israeli analyses played a major role in the US Army's assessment in Israel.

The Sullivan report discusses the September 1992 General Accounting Office (GAO) review of the Army's revised assessment analysis. The panel claims on page 10, "The GAO review states that only about 4 of the Scuds rated by the Army as high confidence warhead kills are supported by '*strong*' evidence [emphasis added, quotation marks original]." The inference by the panel, whether intended or not, is clear – Patriot killed at most 4 Scuds (which would correspond to a 9% success rate). However, this interpretation of the GAO report is both wrong and extremely misleading because the key word "strong" was never used by the GAO.[48] The GAO never said that other Army-assessed kills were based upon "weak" or unsupportable evidence (the implication of the misquoted word "strong"), never established its own "success rate," and never argued that the Army's figures were incorrect.[49] This entire issue, including the importance of sticking to the actual words used by the GAO, was discussed at length six years ago in the panel's one day meeting. That discussion is not even mentioned in the Sullivan report, the importance of focusing on what the GAO actually said is totally ignored and the panel has now adopted the same misleading misquote that was subject to so much criticism six years ago.

The Army's Two "Unknown" Scud Outcomes

In commenting on the Army's scoring, page ten of the Sullivan report states "Two engagement outcomes were scored 'unknown'." Unfortunately, although it was discussed at the panel's 1993 meeting, the report omits mentioning that these two events were de facto scored as failures. The Army's success rates were computed by dividing those engagements that were judged as successful by the total number of Scuds that Patriot should have been able to engage. In an attempt to be somewhat conservative, the Army *included these two events in the denominator of their scorecard*, when in fact, they would have been justified in removing them and raising the score by a few percentage points.

Ballistic Coefficient, Scud Fall Times and Engagement Altitude

The panel reports on page 27 that "The leading visible object in the videos falls at a rate that is consistent with it being a non tumbling Scud warhead section," They identify that "rate" as one derived from a fall time "... on the order of 10 s ..." from "an initial altitude of 11 km." Further, P&L report in their 1993 paper on this subject[50] similar observed fall times of 8.9 to 15.5 seconds for a group of 12 intercepts timed from the videos. The panel then affirms the calculations performed by P&L showing that these altitudes and fall times are consistent with expected values of warhead ballistic coefficient. All of this is used to conclude that the leading visible object is, in fact, the warhead, that the first intercept attempts occurred at altitudes of 10 to 12 km, and that the warhead velocity is on the order of 2.2 km per second, all of which in turn provides a rough calibration for video jump distance.

In its commentary, the panel limits its attention to merely verifying that the P&L analyses and conclusion are consistent with the facts. Once again, however, they do not consider the existence of *other* equally consistent scenarios. We present the missing assessment here by considering a variety of engagement scenarios and then show the wide range of realistic conditions that are all consistent with P&L's fall time observations, including lower intercept altitudes and much slower RV velocities.

Using a set of standard aerodynamic prediction tools and data sources, we estimate the zero-lift drag properties of both the intact Scud airframe and the separated warhead. For comparison, we convert the drag coefficient to ballistic coefficient using the panel's definition and show the results in Figure 3. The mass and diameter of the intact airframe and the separated warhead are the values reported by the panel in their Appendix B (300 kg for the warhead, 2100 kg for the intact Scud, and 0.88 m diameter for both).

Although the panel characterizes the approximate ballistic coefficients of the intact Scud (3000 - 3500 psf) and the non-tumbling warhead section (1200 psf) as single numbers,[51] in actuality, ballistic coefficient is a strong function of Mach number and to a lesser extent, altitude (via the Reynolds number). This dependence is clearly seen in Figure 3. Our estimated values of ballistic coefficient are in general agreement with the single values presented by the panel at the higher Mach numbers, but differ dramatically at the lower Mach numbers where the final part of the reentry occurs, especially for the separated warhead.[52] This large variation in ballistic coefficient during reentry casts serious doubt on the validity of any flight predictions that represent ballistic coefficient as a single constant value throughout the flight, *particularly predictions about fall time and velocity over a potentially wide range of altitudes.* Neither P&L nor the panel provides enough detail to determine whether or not they actually used fixed values to characterize ballistic coefficients, but their results lead one to believe they did.

We have used our variable model of the ballistic coefficients for the intact Scud and the separated warhead in a high-fidelity flight simulation to predict typical reentry trajectories. A sample plot of velocity vs. altitude is shown in Figure 4 for the case of the non-tumbling warhead that has separated from the Scud at an altitude of 50 km.[53] The relatively low ballistic coefficient of the warhead section causes a rapid slowdown once the dense lower atmosphere is reached (20 km and below) yielding an impact velocity of about 0.3 km/sec. Further, a velocity of about 1 km/sec is predicted as the warhead passes through 5 km of altitude, the flight condition chosen for our example of intercept video in the section above entitled "Terminal Encounter Video Evidence and 'Clear Misses'."

Finally, a series of flights was simulated to generate parametric curves of fall time vs. initial altitude for four different Scud reentry situations: an intact Scud and three cases of separated warheads with breakup altitudes of 5, 12, and the 50 km upper bound. From these parametric curves, shown in Figure 5, it is clear that although P&L's reported fall times of 8.9 to 15.5 seconds are certainly consistent with a Scud warhead falling from 10 to 12 km, these fall times are also consistent with a much broader array of scenarios ranging from an intact Scud falling from higher than 21 km to a separated warhead falling from less than 3 km. In fact, the fall times encompass every possible Desert Storm intercept possibility, and then some, for every conceivable Scud breakup situation. The fact that the measured fall times are consistent with the situation P&L choose to analyze is a given – *the fall times are consistent with nearly any situation one might choose to analyze.*

Patriot Warhead Fragments and Disabled Scud Warheads

Are there plausible mechanisms for the in-flight disabling of a Scud warhead

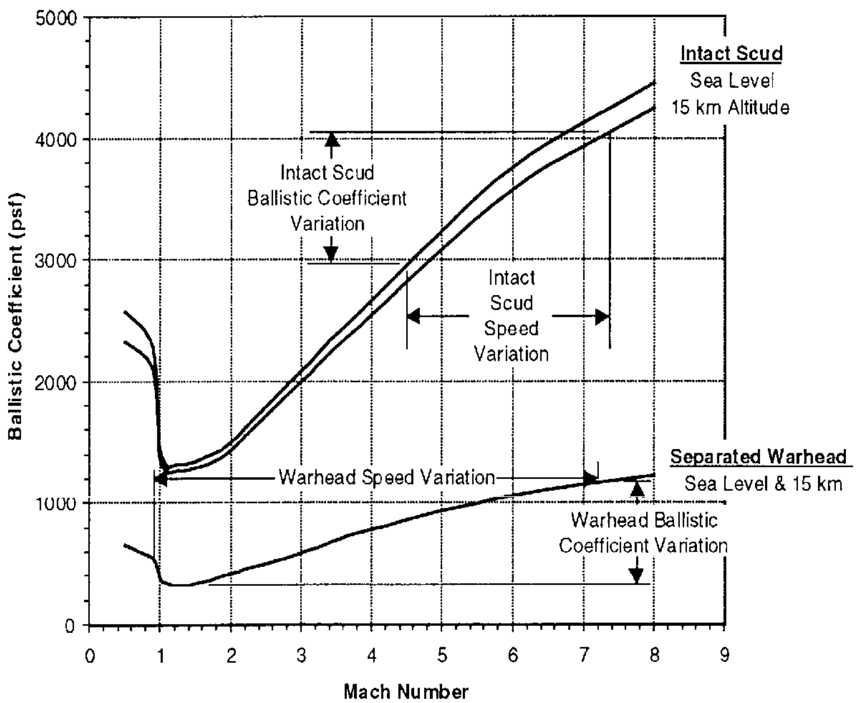

Figure 3: Estimated Variation in Ballistic Coefficient Experienced by Intact Scud and Separated Warhead During Reentry.

by Patriot? Certainly. Scud warheads contain vulnerable areas such as the fuze, battery and associated electronics besides the high explosive. If a single Patriot warhead fragment hits and destroys any one of those critical components, the warhead will not detonate. Sometimes the high explosive itself can be damaged by perforating its casing, causing it to burn in flight, or preventing it from achieving a high-order detonation on impact. The panel appears to accept P&L's argument that, despite recovering a Scud whose warhead was disabled and that the intercept video shows as a fireball overlap with no associated ground flash, "it is unlikely that Patriot warhead fragments could have

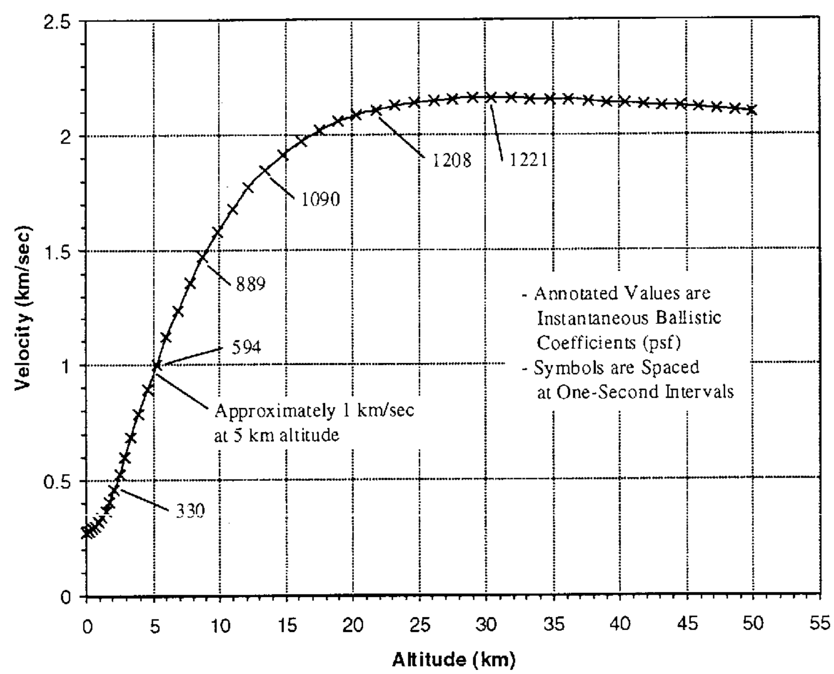

Figure 4: Separated Scud Warhead in Free Fall from 50 km Altitude.

reached the fusing mechanism located behind the warhead without passing through and driving to detonation the high explosive in the Scud." [54] (P&L actually are a little less definitive and characterize this as "low probability.") It is this argument that leads P&L to classify even this engagement, despite meeting all of P&L's success criteria, as a "failure." However, P&L's argument is wrong, the panel's lack of critical comment notwithstanding.

P&L's argument is described in detail in Appendix C of their "Video Evidence" paper (see our note 26). In that appendix they describe the pattern of the Patriot warhead fragments in the Scud rest frame as a conical volume

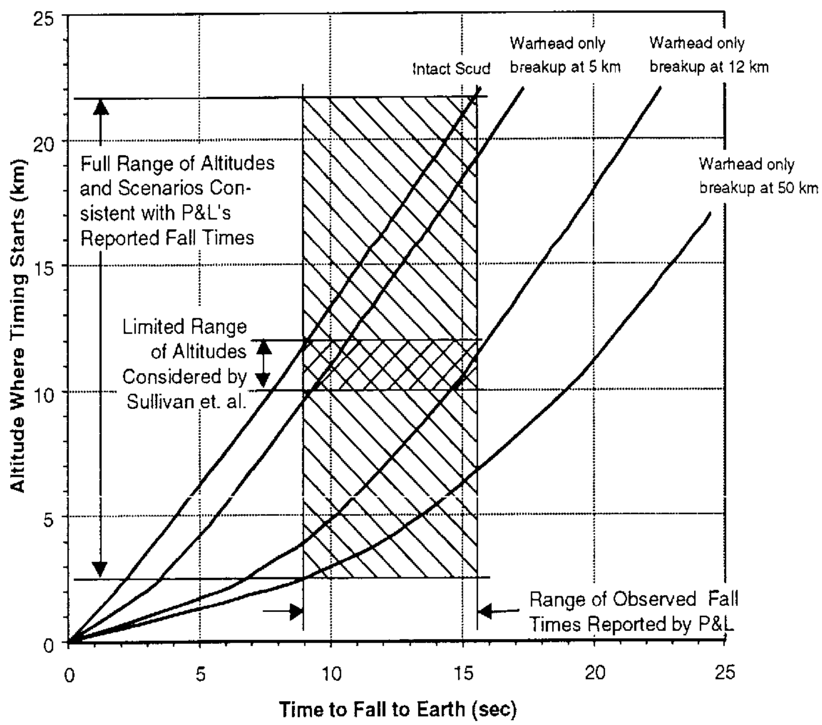

Figure 5: Complete Range of Altitudes and Scenarios Consistent with Observed Fall Times Greatly Exceeds that Considered by the Sullivan panel.

with a 46° half angle. However, the pattern of Patriot fragments in the Scud rest frame actually consists of a more complex volume, described as that encompassed by the space between two cones, not necessarily co-linear and not necessarily aligned along the Patriot missile axis. The details of that spatial pattern are determined by a number of factors, including the Patriot missile velocity, the Scud velocity, the crossing angle of the engagement (not necessarily anti-parallel) and the Patriot missile angle of attack at the time of warhead detonation. In general, only one small region of this 360° dynamic fragment pattern will lie in the direction of the target, and the specifics of that region will depend upon the details of each individual end-game encounter. What matters are the specifics of the closest approach separation vector (early bird, late bird, right or left)[55] coupled with the specifics of the end-game engagement geometry. Because of the highly non-linear causal relationship between these geometries and conditions and end-game lethality, one cannot take a lot of individual averages or representative cases (e.g., the average crossing angle is zero, the average angle of attack is zero, etc.) and put them together to get a "typical" end-game situation (see note 42). The net result of all of this is that P&L's average 46 degree strike angle case, upon which they base their argument, means nothing. Actual fragment strike angles vary from zero degrees to more than 80 degrees over the range of representative end game situations that were encountered in Desert Storm.

The statement about the improbability of being able to disable warhead components without detonating the high explosive is also incorrect. Vulnerable Scud electronic components lay both in front and behind the high explosive. Those in front could be destroyed by any of the Patriot fragments over their possible 80 degree incident strike angle span and those behind by nearly two thirds of these possible strike angles. Thus, many encounters did indeed have the potential to destroy vulnerable Scud warhead components without fragments necessarily having to pass through the high explosive. We submit that the panel's lack of critical comment on P&L's incomplete parameter exploration, overly simplified geometries, important missing factors, Scud vulnerable area modeling and overall lethality conclusions does a disservice to the understanding of this important subject.[56]

SIGNIFICANCE OF THE PATRIOT DEBATE AND THE USEFULNESS OF P&L'S VIDEO ANALYSIS

In their section "Overall Conclusions Concerning the Video Analysis" the panel argues on page 32 that "The Army should have made use of the technical information available in the commercial video tapes. . . ." In fact, the Army did make use of both commercial TV and infra red video tapes in their assessment of Patriot performance *to the extent that the Army felt the videos were technically useful*. Was it technically useful to see that sometimes Patriot warheads detonated late? Perhaps so, but the fact that the Patriot warhead and fuze were being employed over a wider area against faster missiles than the system had been designed to handle and would sometimes result in late fuzing was first raised by the Army, *two years before P&L's first paper on the subject.*

Was it technically useful to see that sometimes Patriots chased false targets because target breakup had not been anticipated? Perhaps so, but this fact was known instantly on the battlefield and fixes were conceived, designed, tested and installed in weeks. Was it technically useful sometimes to see a fast moving dot of light emerging from a fireball, a dot of light which nearly nine years later still cannot be explained in terms of its underlying physics? Perhaps so, but no one in either the Army or industry expected Patriot intercepts, even when successful, to disintegrate 4000 pound Scuds. Was it technically useful sometimes to see a few frames of a flash of light on the ground after a Patriot intercept attempt? Perhaps so, but even now the causes of those flashes and the ability to use them to differentiate high order explosions from fuel/air combustion and kinetic impacts are still debated by reputable physicists. And does anyone really believe that those few frames of optical emissions with unknown causes are more informative than the on-site ground damage investigations, however imperfect, performed almost daily by Israeli, US Army, and Saudi Arabian investigation teams? High order explosions may be ambiguous on video tape taken from miles away, but there was no ambiguity when a Scud detonated high order in Tel Aviv, Dharhan or Riyadh.

The Army's assessment analysis credits Patriot with an overall success rate of 60% when the two theaters of operation are combined.[57] Based upon the lessons learned from that conflict and a desire to do better against new threats, the US government has made two block improvements to Patriot and a third is being deployed now. Patriot no longer resembles, from an operational performance standpoint, the Patriot of early 1991. In addition, three other TMD systems are being developed and over the next decade or so will complement Patriot's capabilities. These systems, in combination, will ensure that defenses can be injected on land or sea wherever and whenever necessary and that at least two fully independent engagement opportunities, based upon fundamentally different technologies, intercept altitude regimes and phenomenologies, will be brought to bear on any TBM threatening a defended area. Would this evolution have proceeded very differently if the Patriot score had been slightly or even significantly less than that assessed by the Army? Probably not. This evolution in TMD capabilities was determined from the existence of a real threat, real vulnerabilities, real military needs and funding availability.

The final section of the Sullivan report attempts to rise above the fray and recap what to the panel are the high level lessons learned from all of this.

- *Both knowledgeable and independent people should be involved in assess-*

ing capabilities. We certainly agree.

- *Data gathering of a weapon system's effectiveness should be as thorough as possible*. Of course, and in Patriot and other systems that process has been automated.

- *People with technical backgrounds should be available to support military operators of modern "high-tech" systems in the field during wartime when the need arises*. Absolutely, and in fact, such people did provide critical technical support to the military operators of a number of systems, including Patriot, during Desert Storm.[58]

- *The development process of complex systems should be less "linear" and allow continual feedback of the results of both field testing and combat experience*. Certainly and that is what the recent trend to Advanced Concept Technology Demonstrations, Block Upgrades and Near-Real Time Battlefield Adaptation are all about.

- *There will still be surprises*. Of course. We must anticipate them as best we can, understand them when they occur and be ready to respond rapidly and effectively when necessary.

These are the important issues and the ones highlighted in the final "Lessons Learned" section of the Sullivan report.

SUMMARY

We neither conclude nor assert that every engaged Scud was defeated by the Patriot missile defense system. Indeed, we know that live Scuds did indeed reach the ground in Israel and Saudi Arabia where they exploded, causing extensive and sometimes severe damage. We agree with the panel that P&L's scoring of the limited number of engagements they studied is profoundly different from our own conclusions about the success rate of the Patriot.

Our disagreement with the panel is on the question of whether the P&L analysis is, in every case or even most cases, more probable than alternatives proposed by us and by others. Certainly some of the events P&L believe are misses are misses; Scuds are known to have exploded on the ground. However, we do not agree that the panel's conclusions about specific outcomes are always, mostly, or even frequently correct.

As an example, we agree that a number of videographed ground flashes show Scud warheads exploding. With only a few exceptions we would agree that all of the video imagery of ground flashes is *consistent* with what would be expected from such events given the limitations of the video cameras and tapes. But for pictures of an event to be *consistent* with one explanation does not mean that the explanation is true or that the pictures are *inconsistent* with other explanations. We have demonstrated that events which P&L associate with only clear misses (no fireball overlap) can, in fact, be successful intercepts. And we have shown that the recorded time for a Scud to reach the ground can be consistent with a very large range of representative initial observation altitudes, intercept altitudes, and ballistic coefficients – not merely the set of parameters endorsed by the panel.

As another example, there are events in which evidence of significant ground damage is absent, or where recovered Scud debris indicates that it has been struck by Patriot warhead fragments and the Scud warhead did not detonate. We submit that the totality of the data for such engagements must favor an interpretation that the observed flash was not the result of a high-order explosion of a Scud warhead. Since such events are *known* to exist, the P&L hypothesis endorsed by the panel that a ground flash *implies* a Scud warhead explosion must fail.

Indeed, our fundamental disagreement with the panel is that they have merely asked if the conclusions of P&L are consistent with the information recorded by television news cameras. If the P&L analyses seem consistent with the tapes, then the panel accepts P&L's conclusions.

The battle in space above Israel and Saudi Arabia is, however, one in which the totality of the data for any one engagement is often insufficient to single out the correct answer from among two or more quite different plausible conclusions. Each conclusion is grounded in the data set, and several plausible explanations are true, but for different subsets of the data. The panel fails to recognize that two or more mutually exclusive arguments can be consistent with the available videotaped data and that the televised information may not suffice to reach a conclusion.

The evidence available for some events inclines the analyst towards the conclusion that a Scud was defeated, for example when recovered Scud debris showed evidence of Patriot warhead fragment-sized holes penetrating the shell, and when no ground damage was reported. Such information is of a quality to force one to decide that any flash occurring upon Scud impact did not come from a high-order detonation of tritonal.

The presence of extensive ground damage, in contrast, should bias the analyst in favor of accepting the conclusion that the Scud penetrated the defensive screen.

It would be as foolish to argue that all events with, for example, ground flashes represent failures of the Patriot to intercept its target as it would to argue the converse, that all such events represented successful intercepts with the associated flashes coming from mechanisms other than the detonation of the Scud warhead. We make neither case, and we encourage Sullivan and his co-workers to reconsider their argument that events which are consistent with Postol's and Lewis's analyses *necessarily* are correctly explained by those arguments.

All of the above notwithstanding, the panel has nevertheless derived some important and broadly applicable lessons learned from the Patriot experience in the Gulf. They do not depend upon any particular score, they do not depend upon any particular interpretation, they do not even depend upon news videos. They are common sense and we agree with all of them.

APPENDIX A

Distinguishing Successful and Unsuccessful Intercepts on Video Imagery

Because the panel, and P&L earlier, have placed great emphasis on the emergence of a point of light from a region of the Scud trajectory obscured by the Patriot fireball, it is important to examine the likely appearance on commercial video of an event in which a Patriot fragment either fatally damaged or actually detonated the Scud warhead. Let us concentrate initially on the subject of detonated Scud warheads.

The first question an image analyst must pose is whether or not the videographer has tracked an object which contains the Scud warhead (for example, a Scud airframe with attached warhead accompanied by the combustion of leaking fuel to provide sufficient light to be recorded). As is mentioned in note 11, a warhead detached from the airframe is not likely to be luminous at the altitudes where intercepts took place. Since all of the P&L analysis depends upon reconstructing the trajectory of the warhead itself, it is presumed in what follows that the visible track is of an object which is attached to the warhead.

It would be useful to be able to track the Patriot missile as well as the

Scud, but the Patriot does not travel fast enough to be luminous because of air friction. After rocket motor burnout the Patriot is dark, and its position can only be inferred at the instant of detonation when the explosion products produce enough light to be detectable. Thus, for a video frame recorded in the first few milliseconds after detonation, we need to know whether the separation between the spark of light from the explosion and the luminous track of the Scud would be sufficiently distinguishable to record the two as distinct objects. We will assume a "best case," i.e., one with a linearly responding TV camera with near-perfect optics and no CCD "bloom" to cause output from a dark charge coupled device adjacent to an illuminated one.

A high quality video camera has about 40 CCD elements per millimeter corresponding to a 20 line pair per millimeter resolution in the focal plane. Such a picture element (pixel) is about 0.025 mm square. A reasonable estimate for the focal length of the camera lens is 100 mm if hand held or 500 mm if the camera was tripod mounted. The slant range from the camera to the point of detonation is unknown, but a reasonable estimate would range from about 7 to 15 kilometers depending upon the altitude of the engagement and the distance of the camera from the intended target of the ballistic missile. The magnification, m, of the optical system is the lens focal length divided by the slant range, d. For the optimum combination of long focal length and low slant range,

$$m = 0.5/7{,}000 = 7\text{x}10^{-5}.$$

For the least favorable situation, short focal length and long range,

$$m = 0.1/15000 = 7\text{x}10^{-6}.$$

If the Patriot fuzes at a distance of 10 meters from the Scud, and if that geometry is undiluted by viewing angle, then the separation between the images of the Patriot detonation and the Scud on the focal plane of the camera ranges between $7 \text{ x } 10^{-1}$ mm and $7 \text{ x } 10^{-2}$ mm. In the first instance several pixels would intervene and the task would be easy. In the second case, the task is difficult and only with a mathematically ideal camera in the absence of diffraction and scattering effects would it be possible to distinguish the two objects.

However, matters are not so simple. The calculation implicitly assumed that the Patriot detonation illuminated no more than one pixel, as did the Scud. This is improbable, even if the detonation were imaged very shortly after it occurred. While the Airy disk of any good zoom lens should be comparable to the size of a pixel, although it is in fact usually larger, it is not the case that the point spread function of the lens can be ignored. Indeed, a finite-sized image of a point of light is certain to affect more than one pixel, depending upon its placement on the focal plane. Taking diffraction into account we know that some light from the detonation must illuminate several adjacent pixels even without "blooming" of the CCD response. Similarly, the light from the Scud will also be spread over a number of pixels, even if concentrated on a single one.

Other optical aberrations in the lens may be of even greater importance. Video lenses rarely must resolve more than 20 line pairs per millimeter in the focal plane, because that is the size of the sensors, rather than the 80 line pairs per millimeter which can be resolved on processed film using a high quality 35 mm camera lens. Most TV cameras use zoom lenses with very many elements, so that internal flare from a bright source cannot be neglected, particularly when the source is seen against a black sky -- precisely the case at issue.

Therefore, we conclude that it is possible but unlikely that a Patriot detonation, imaged within the first few milliseconds before the fireball expands to meters in size, would actually appear as a point of light cleanly separated from the Scud. Given the improbability of imaging the Patriot fireball at such an early stage (particularly if the CCD has an integration time comparable to its frame interval of almost 33 ms), it is most probable that the Scud and Patriot detonations will affect an overlapping set of pixels. Thus, if the Patriot caused the Scud warhead to detonate catastrophically, then it is certain that both phenomena would overlap as recorded by a video camera.

The only way to identify a catastrophic detonation of the Scud while the Patriot and Scud fireballs are visible would be by the size of the combined fireball, which should appear larger than the Patriot can produce alone. However, P&L have described apparent fireball sizes as large as hundreds of meters in diameter, with minimum diameters significantly greater than the 25 m physical fireball. Since the physical diameter of the fireball depends on the energy density within it (the outer edge of the fireball must be heated to luminescence), it follows that doubling the actual diameter requires an eight-fold increase in the explosive energy released. The Scud warhead is not eight times as energetic as that of the Patriot, nor is the video-apparent fireball diameter necessarily related in any scalable way to the physical diameter.

The video-apparent fireball diameter may be partially accounted for by the presence of burning particles of explosive or the scattering of light from ejected non-combusting particles, but if that is so, then only the high velocity tail of the velocity distribution of particles is available to produce the video-apparent fireball because particulates are stopped in a finite distance depending on atmospheric density and initial velocity, not total high explosive energy. Indeed, they lose speed exponentially with the distance from the explosion and so, for all practical purposes, come to rest at a distance independent of the characteristics of the explosive. It follows, therefore, that under this explanation, the video-apparent diameter must increase much less rapidly than the cube root of the energy and the difference between a Patriot-only and a Patriot + Scud fireball will be even less discernable.

If the apparent fireball diameter is largely a function of the electro-optical system of the camera, then it is not likely that the cases of Patriot-only and Patriot + Scud detonation can be distinguished, even using the in-camera video tape, because the true differences are swamped by the camera's electro-optics properties. This is the probable case.

We conclude that it is not possible to distinguish the cases on the basis of the appearance of the fireball. One is left, therefore, with an examination of the debris exiting the fireball as a means to identify catastrophic detonations, as opposed to Patriot intercepts which merely damage the Scud so much that the ballistic missile's warhead cannot explode "high order" on impact with the ground, and clean misses.

Postol and Lewis, as well as the panel, make much of the fact that a bright object is seen to emerge from the fireball on approximately the same trajectory as the entering object. However, the Scud would be neither annihilated nor vaporized by the explosion of the (roughly) 200 kg warhead it carries, and many components of a Scud are heavy enough to survive the explosion. Further, the momentum imparted to the surviving dense objects (e.g. rocket thrust chamber, blow-down bottle, turbopumps, etc.) would not cause significant visible deflection from the entry trajectory in the first few frames after detonation. Rather, the deflections, when they occur, are surely caused by changes in the Scud's aerodynamic properties.

Therefore, we conclude that it is improbable, and perhaps impossible, that Postol and Lewis could have identified a Patriot-caused detonation of a Scud warhead on the basis of the images recorded on videotape at the time of the engagement. Further, we conclude that the mere presence of a high speed bright object exiting the region of the video-apparent fireball does not demonstrate a failure of the Patriot to inflict sufficient damage on the Scud to prevent its high order detonation and is irrelevant to scoring the success or failure of the engagement. If *either* the trajectory or the appearance of the emerging bright object (not necessarily both as P&L demand) change after its encounter with a Patriot, then that should be considered to be affirmative evidence of a hit (although the contrary is not necessarily true, i.e., a lack of change should not necessarily, in and of itself, be equated with a lack of a hit). And if that change is followed with an absence of significant ground damage, then that should be considered to be reasonable evidence of a successful intercept.

In fact, however, it is not clear how many Scuds detonated in flight after being struck by fragments from a Patriot warhead (the videos, as we have discussed, are not reliable indicators). Many, or perhaps even most of the actual damage mechanisms were far more subtle, as we discussed in the body of our paper, and would not have been visible even in the highest quality imagery. Commercial video imagery of the engagement region does not provide sufficient information to distinguish any one of the three possible cases -- Scud detonation, Scud warhead neutralization, and a close but clean miss -- from any other.

NOTES AND REFERENCES

1. The preliminary 1993 panel report (Jeremiah Sullivan et al., "Report of the POPA Ad Hoc Panel on Patriot and Theater Missile Defense," 14 September 1993) stated that the publication of a short article "would improve understanding . . . of the substantive issues in the Patriot debate," but cautioned that "The preparation and ultimate publication of [an] article would require cooperation from Army-Raytheon and the MIT group." Unfortunately, to our knowledge, during the intervening five years between May 1993 and release of the draft Sullivan report, no one critical of the Postol/Lewis analyses was ever informed of the ongoing Sullivan panel work, asked if they wished to participate with the panel, invited to expand upon the material presented five years prior, or answer any questions. In contrast, note 32 of the Sullivan report states "During the long course of the preparation of this paper, Postol and Lewis have . . . answered numerous detailed questions about all aspects of their work."

2. As discussed subsequently, these four events (A2, A10, A12 and A13 in table A of the Sullivan report) depend solely on a large video-apparent miss as the criterion for scoring the event as a failure.

3. On page 17 the panel states "if the apparent miss distance is large enough, the video data provides *unambiguous* evidence of a miss [emphasis added]." "Large enough" for what is not explained, assuming that they mean something more fundamental than the circular argument that if the miss is large enough to be unambiguous, then it is unambiguous. Whatever the intended meaning, in their report the panel de facto equate "large enough" to the absence of what is called a "fireball overlap," and for which they accept P&L's designation of a "clear miss." We show, by providing a counter example, that the absence of a fireball overlap does not unambiguously depict a failure over the relevant miss distance ranges of interest.

4. Some have argued for years that this debate and its clear resolution are of fundamental importance to the future of theater missile defense. We do not subscribe to this "fundamental importance" argument and will show that even if P&L were correct, which we do not believe, the evolution of theater missile defense would not have been significantly affected over the past nine years.

5. The panel states on page 33 that their current level of understanding does not permit extrapolation of Patriot performance in the Gulf to the upgrades made since the war, which they identify incorrectly and describe only partially (see our section on "Errors and Omissions"). On page 34 they say nothing they studied bears directly on the performance of either the additional planned upgrades to Patriot or any other future missile defense systems.

6. This is not their criterion per se (they talk in terms of three "jump distances") but, de facto, in terms of all of their videos and analyses, the "fireball overlap" turns out to be a nearly equivalent criterion.

7. We exclude 2 events from this categorization – A15 and A16 in the Sullivan report's Table A – because both of these events are associated with another intercept attempt that is hidden behind clouds and thus cannot be judged based upon there being nothing other than "clear misses."

8. We include event B5 in this category even though the panel, based upon the fact that P&L don't know whether or not this Scud was within Patriot's defended area, designate this as an "other" rather than a "failure." We include it because the panel states on page 20 that, other than the defended area uncertainty, they would have scored this as a failure based upon the existence of the ground flash.

9. For this engagement, after passing the clear miss, emerging object and ground flash criteria, P&L invoke, according to the panel three reasons for failure: 1) their argument that Patriot fragments cannot disable a Scud warhead without detonating the high explosive (shown to be wrong in our "Errors and Omissions " section on "Patriot Warhead Fragments and Disabled Scud Warheads"); 2) the fact that the Army has not made public any evidence that Patriot caused the disabled warhead; and 3) information from an unnamed source.

10. According to the Sullivan report's interpretation, P&L use the emergence on an unchanged trajectory of a fast moving dot of light from the fireball as a rationale for classifying an engagement as a failure, even if a fireball overlap occurred, no evidence of a ground flash was present and no evidence of ground damage ever existed (see Scuds A5, A14 and A17 on page 19 of the Sullivan report). Although the report discusses the significance of changes in the qualitative appearance of the ball of light pre

and post intercept, this doesn't appear to have had real import in P&L's scoring. A5 and A14 look qualitatively the same, A17 looks qualitatively different and all three are scored as failures based upon the trajectory.

11. On pages 24 and 25, the panel goes through a series of possible explanations for the existence of a glowing object in the videos and one by one rules them out (e.g., "it seems certain that warhead heating due to air friction alone can not be the primary source of the optical emissions seen in the videos"). The only real conclusion they reach is the same one that any layperson would arrive at simply by viewing the videos without any analysis. ("Nevertheless, it is a fact that there is something visible that descends quite rapidly all the way to the ground in almost all the videos.")

12. The question they choose to investigate (on pages 27 - 29) is "Are the observed ground flashes consistent with what would be expected to be seen on a commercial video of a Scud warhead explosion (detonation) viewed from a distance?" One might have expected them to address the question "What are the possible sources of ground flash as observed on commercial video?" or "How do alternative explanations of ground flash as observed on commercial video compare to each other?" Unfortunately, they briefly consider only one other possible source of ground flash and never discuss at all the possibility of a flash from a purely kinetic impact.

13. The panel briefly discusses the possibility of residual fuel burning or exploding on the ground, either from attached or detached tanks. However, they dismiss this explanation based upon an incorrect definitional argument about duds and their assertion that "except for the three known duds, all warheads must have detonated on impact." This argument, the fallacy of which we discuss below, leads them to discount the possibility of burning fuel. ("Thus, the burning fuel mechanism fails as an alternative explanation.")

14. The panel mentions these LOSAT videos, but in a different section of their report (page 23) dealing with the debate's history and the analysis of Zimmerman. Zimmerman became interested in and subsequently critical of the video analysis of Dr. Postol after he appeared on television in 1991. Zimmerman testified before the House Government Operations Committee and presented his findings to the panel at its May 1993 one day meeting. Unfortunately, other than noting that Zimmerman changed his view on the one issue of video-apparent fireball diameters, the panel fails to deal with or even acknowledge the bulk of Zimmerman's arguments.

15. See page 27. They acknowledge the possibility of a third option -- that of a damaged warhead with greatly reduced yield, similar to the burning of a firecracker when it has been ripped open -- but dismiss this as numerically insignificant since "the Army reports only two cases of this in the Gulf War."

16. See page 27. Only three of these four Scuds were engaged by Patriot and on only one of these three do P&L have videos all the way to the ground. The panel appears to place great significance on the fact that this one video shows no ground flash (it is emphasized with italics). They stop short, however, of absolutely generalizing this one case to all disabled warheads (or its inverse – i.e., the presence of a ground flash -- to fully functioning warheads).

17. Despite the panel's comment on page 10 that "it is not clear from the public record if actual Patriot fragments were found in recovered Scud warheads," such evidence of Patriot fragment holes (no fragments, as they are small and would likely have broken up or fallen out) and missile parts in recovered warheads was specifically discussed at the ad hoc panel's May 1993 meeting.

18. These consist of A5, A14 and A17 in criterion three; A6, A8, A15, A16, B2, B3, B4, B5, B6, B7, B8 and B9 in criterion four; and A4 and B10 in "other."

19. Consideration of events with evidence of "only clear misses" would actually consist of eight events (the panel's F1, F2 and F3 cases in Table A minus A15 and A16). Eliminated from the 29 total events would be all 12 events in the panel's Table B; the seven events in Table A which have at least one fireball overlap and for which nothing about "miss" can be determined (A4, A5, A6, A8, A11, A14 and A17); and events A15 and A16 in Table A, both of which have at least one engagement obscured by clouds. That leaves eight events, four of which (the panel's F1 cases) are associated with heavy ground damage (and are therefore uncontested) and four of which (those discussed here) are not.

20. The proposition that a clear disagreement between the Army's assessment and Postol's "clear miss only" cases existed on only two engagements was discussed with the panel at their May 1993 meeting. Although they referred to this proposition with interest in their September 1993 preliminary report, they do not mention either that discussion or proposition in their 1999 report.

21. On a number of occasions the panel waves aside entire classes of events based on the fact that, in each case, the number of events involved is small. These include consideration of impacting Scuds that didn't break up (they assume the numbers are small but have no direct evidence -- page 5 and note 7); Patriot fireballs that appear ahead of the dots of light believed to be Scuds (page 27); Scuds that impacted and burned low order (page 27); and engagements the Army classified as "mission kills" (page 31). Unfortunately the number of engagements analyzed by P&L is not large to begin with, and the specific classes of video evidence upon which P&L rely for their assessment are quite small (e.g., miss-related: four, fast emerging object related: three, ground flash-related: twelve). In such a problem of small sample sets, one has to be very wary of discarding entire classes of events based upon "small numbers."

22. P&L actually include eight events with "only clear misses." We focus on these four because the other four are associated with extensive ground damage (our category one), a much more reliable criterion for intercept failure, and would not be the subject of disagreement between P&L and the Army.

23. We say "approximate" because the actual detonation of the Patriot warhead could occur anytime within the typical $1/30^{th}$ of a second frame interval of the video cameras. In this $1/30^{th}$ of a second time interval, the Scud and Patriot missiles can move relative to each other by more than three hundred feet. Since relative positions of tens of feet are of interest in terms of establishing success or lack thereof, this interframe movement, as well as a number of other factors, has to be compensated for. This is the area in which P&L have done the most extensive work.

24. Angle of attack is the angle between the missile's centerline and its velocity vector. The Patriot missile routinely approaches 30 degrees of angle of attack during the final moments of an intercept. Both P&L and the panel ignore the impact of angle of attack on end-game lethality.

25. On page 14, the panel states " . . . Postol and Lewis introduce an apparent 'miss distance' by drawing a straight line in frame 1 from the Scud warhead section to the centroid of the video fireball, and they measure the length of this line in units of the video jump distance. We will refer to the length of this line as the Postol-Lewis miss distance (PLMD [sic])." Further on they state: "We define the 'true Postol-Lewis miss distance' (MDPLT) as the length of a three-dimensional vector drawn from the centroid of the Patriot fireball to the position of the Scud in frame 1 . . . hence MDPL = MDPLT $\sin\alpha$ . . ." i.e., the true straight-line distance (after removing the two dimensional geometric dilution caused by the camera viewing angle) from the Patriot warhead location to the location of the Scud in the first video frame after detonation. Also, on page 15 they state: "The *true miss distance (MDT)* is the length of a line drawn from the centroid of the Patriot fireball and the position of the Scud warhead . . . at the instant the Patriot interceptor fused." (This parameter cannot be obtained from the videos.) These statements all illustrate a misconception by the panel that miss distance and the separation between warhead and Scud at detonation are the same.

26. George N. Lewis and Theodore A. Postol, "Video Evidence on the Effectiveness of Patriot during the 1991 Gulf War," *Science & Global Security* (1993): 4:60-61.

27. The desired intercept geometry for the end-game depends on a number of factors and involves a complex trade-off between guidance performance (favors near-anti-parallel), warhead performance (favors high crossing angle to achieve a fragment strike angle that is large, relative to the target missile longitudinal axis), missile maneuver capability (favors anti-parallel), and fuzing constraints (favors moderate crossing

angle). This trade generally results in the optimum intercept geometry being nearly but not quite anti-parallel with a relatively broad region of good performance around the optimum.

28. We do not mean to imply that P&L's end-game video methodology is incorrect always or even a majority of the time. We simply show that situations exist, perhaps similar to the two successful intercepts scored as "clear misses" and discussed previously, in which P&L's methodology has the potential to yield the wrong answer.

29. We have defined a "successful intercept" in this context as one in which Patriot warhead fragments impact vulnerable armament areas on the target with sufficient energy and obliquity angle to penetrate. The scenario in figure 1a does not meet this criterion while the scenario in 1b does. Modeling was performed against an Al Hussein unitary warhead (i.e., no submunitions) using a Raytheon simulation that includes the impact of closing velocity, crossing angle, fuze range, fuze look angle, number of fragments on target, fragment strike angle, fragment impact velocity, and Patriot angle of attack. Since many of these individual parameters are not available for public release, they are discussed here only in their aggregate.

30. This is not the "typical" Scud velocity modeled by P&L in their analysis, but it is well within the range of actual Scud velocities encountered in Desert Storm over the range of actual intercept altitudes. Failure to consider these "non-nominal" situations is one of the many oversimplifications limiting the applicability of P&L's work. In fact, contrary to the generic case from which P&L derive target velocity and contrary to what they suggest on page 62 of Appendix C of "Video Evidence," it might have been more effective to try to make intercepts at lower altitudes, the majority of the Patriot intercepts occurred well below the P&L "typical" altitude of 10 to 12 km. This was due to the speed of the RV (higher than the PAC-2 design requirement), the increase in reaction time due to manual operation in Israel (the design doctrine was automatic) and the attempt (in Israel) to "stretch" the defended zone to cover the extended area of metropolitan Tel Aviv. At an altitude of 5 km, even a relatively "high beta" object, such as a non-coning, non laterally accelerating, trimmed (no moments around the center of gravity of the body), detached warhead, will have slowed to about 1 km/sec from the effect of normal aerodynamic drag. We will discuss this further in the section on "Errors and Omissions" later in this response.

31. One of us (Zimmerman) estimated a true fireball diameter of about 10m in his "Report for the House Committee on Government Operations Legislation and National Security Subcommittee on Patriot Effectiveness (Rev 1) and other Related Subjects Concerning Patriot ATBM Performance During Operation Desert Storm". Zimmerman's estimate was based on the energy in the warhead high explosive and the volume of air and afterburning debris which could be heated to incandescence. The panel reports a value in note 38 where they say "An unclassified daytime photo of an inter-

ception at White Sands Missile Range of a Lance missile by Patriot PAC-2 shows a fireball diameter of about 25m." How much of the 25m diameter is an artifact of the camera, even in daytime, is not known. Here, to be conservative, we have selected the larger 25 meter true diameter for our example scenario.

32. Actual lethal miss distance requirements for Patriot are not available for public release. For this example we used the panel's reported value of lethal radius, stated on page 13 as 5 to 10 m, and then established that the end game resulted in meeting the fragment impact criterion of note 29 above.

33. As long as the ratio between miss distance and the camera-to-intercept point distance is large, actual miss distance doesn't matter. What does matter for the "unsuccessful" intercept TV sequence to match the "successful" case is for the point of unsuccessful detonation to lie along the same camera-to-fireball line of sight as in the successful case. An infinite number of anti-parallel Patriot trajectories, each with an arbitrarily large miss distance, can satisfy this criterion.

34. Although the projection of the image onto the video plane would actually consist of slightly convergent rays, the distance of the engagement point to the camera (approximately 7 Km), the small lateral extent of the engagement (40 to 50 meters normal to the camera line of sight), and the limited resolution of this kind of printed material make the projection rays appear parallel in the figure.

35. The panel states on page 17, "In particular, Postol and Lewis classify an intercept attempt as a 'clear miss' and conclude that the Patriot could not have caused damage to the Scud warhead only if the MDPL is three or more times the video jump distance . . . " The panel then agrees with this characterization by adding their own statement that "... the MDPL distribution is bimodal -- every clear miss has a MDPL large compared to the corresponding video jump distance." In our figure 1b scenario the MDPL is 3.8 times the video jump distance, there is no fireball overlap, the fireball is large compared to the Patriot lethal radius (and would be calculated to be even larger) and the intercept is successful!

36. On page 13, the panel states: "The apparent sizes of the Patriot video fireballs seen in the videos (transverse dimensions range from 50-400m) . . . ," and then "No unique explanation has been established for the difference between the video and the actual (true) Patriot fireball sizes.". Finally, they state in note 37: "We refer to the bright regions seen on the videos following explosion (fusing) of the Patriot interceptor as the 'video fireball' to distinguish them from the actual fireballs that had to have been much smaller."

37. See page 13 of the Sullivan report and Pages 4 and 10 of George N. Lewis and Theodore A. Postol, "Video Evidence on the Effectiveness of Patriot during the 1991 Gulf

War" *Science & Global Security* 4.

38. We do not mean to imply that the entire explanation for the large fireball diameters stems from errors in estimated velocity and viewing angle. Certainly that is not the case and these errors work both ways. Other factors involving the camera system, such as the panel suggests, also came into play on occasion. But which factors came into play on which shots and to what relative extent are unknown to everyone concerned -- the panel, P&L and us.

39. They did this by hitting a button on the Patriot consoles that made a hard copy of what is called a "track amplification tab" on the screen of their display. The track amp tab displays, among other things, numerical information about target states. By hitting the button repeatedly, operators got a sampled record of target trajectories, in some cases indicating dramatic changes in heading and/or velocity right after intercept. It does not, however, provide detailed information about Patriot operations. Other records were obtained in Israel from PC recorders (which were used only sparingly because they sometimes caused the system to crash) and from video recordings of the operator screens in Saudi Arabia. The totality of the data collected is still being used today to characterize Scud aerodynamics and breakup behavior.

40. It is incorrect to assume, as the report does, that because the Patriot computer was based on a 1970's design its capability to perform precision calculations was insufficient. As computer technology has advanced, the memory and processing chips used in the Patriot Weapons Control Computer have been updated five times, with throughput and memory respectively now four times and 20 times the original design. All but the last of these updates had been installed prior to the Gulf War, but even before that time, double precision arithmetic calculations were used on all required precise arithmetic routines.

41. Command guidance is used in Patriot only for the midcourse phase. This is when the system tries to put the Patriot missile on an anti-parallel course with the target missile. The most critical phase, however, is the guidance "end-game" during the last few seconds of flight. During this phase the onboard guidance sensor in the missile "homes" on reflected energy from the target, getting increasingly precise relative position information as the separation distance decreases, thereby reducing miss distance far more than is possible with command guidance. This onboard guidance sensor is quite separate and distinct from the "self-contained fusing radar." It comes into operation only in the last fraction of a second and is used solely for the purpose of warhead detonation timing.

42. P&L repeatedly use "averages" or "typical" parameters to describe the Patriot/Scud end game. There are two problems inherent in doing this. First, many of these parameters are not independent of each other -- e.g., in a low altitude intercept at the

edge of the defended zone, the Scud velocity will be low, the crossing angle will be high, the Patriot missile velocity will be low and the angle of attack will be high. The combination of these parameters strongly effects end game lethality and the parameters are correlated, not independent. Thus, the "average" situation may not exist and will certainly not have any significant utility (not unlike the average telephone number, which Tom Lehrer characterized to an MIT audience in 1971 as the world's most useless statistic). The second problem in using averages is that the end game problem is highly non-linear -- small changes in one direction or another of these critical parameters can have a dramatic effect on the success or failure of an engagement. Thus, the "average" situation, even if it existed, does not yield the average result.

43. The details of this analysis of ground damage were discussed with the panel in the one day May 1993 meeting by Stein, but unfortunately, as discussed above, not summarized by the panel. In addition, as noted by the Sullivan report, Zimmerman and the late Charles Zraket both testified in detail at the May 1992 Congressional hearing regarding differences between Postol's use and the correct use of Scud damage statistics. Unfortunately, their positions are not summarized either.

44. Gregory Jones, of the American Institute for Strategic Cooperation, describing the flaws in Postol's ground damage analyses, wrote: "Given these problems it is not surprising that in a more recent publication, Postol retreated from his earlier position. . . But rather than acknowledge his retreat, he attempts to mask it by changing his analysis in a way that lacks a methodological basis. Nor has he improved his arithmetic." Gregory S. Jones, "The Iraqi Ballistic Missile Program: The Gulf War and the Future of the Missile Threat," *American Institute for Strategic Cooperation* (Summer 1992): Appendix 2

45. S. Fetter, G. Lewis and L. Gronlund, "Why Were Scud Casualties So Low?," *Nature (International Weekly Journal of Science)* (January 1993): 362:294.

46. R. Ranger, "Theater Missile Defenses: Lessons from the British Experience with Air and Missile Defenses." *Comparative Strategy* (October - December 1993):12:4, 408 and note 65. This quote specifically references, in note 65, the *Nature* article by Fetter et al.

47. House of Representatives. *Performance of the Patriot Missile in the Gulf War: Hearing before the Legislation and National Security Subcommittee of the Committee on Government Operations*, 102 Cong., 2nd Sess., 7 April 1992; U.S. Government Printing Office, *Statement by Major General Jay M. Garner*, (Washington DC: 1993) ,6 ,7.

48. The 9% figure (from which the panel derived the number of 4 Scuds) comes from a GAO succession of subdivisions of the 60% overall successful intercepts assessed in the Army's analysis and quoted by then Secretary of Defense Richard Cheney in 1992 (see

our note 54). The first subdivision of the 60% is into "warhead kills" (52%) and "mission kills" (8%). The GAO examined only warhead kills. The second subdivision is that of parsing the warhead kills into the three confidence levels established by the Army. About one half of the 52% warhead kills were in the Army's highest confidence level category (25% of the overall engagements). It was only this group of 25% that the GAO examined. Within this 25%, the GAO established that approximately one third (9% of all engagements) had what they considered to be the "*strongest* evidence [emphasis added]." The word "strongest" is what actually appears in the GAO report (United States General Accounting Office, Report to Congressional Requesters, *Operation Desert Storm,* 1992, GAO/NSIAD-92-340, 4), followed by a definition of the two types of evidence which the GAO considered "strongest" (a recovered Scud with Patriot fragments or fragment holes in it or radar data showing evidence of Scud debris following an intercept). The presumably careless substitution by the panel of the word "strong" for the GAO"s actual word "strongest" totally changes both the context and the meaning of the GAO's statement.

49. The panel states on page 10 "the other 7 Scuds [16%] scored by the Army as high confidence warhead kills are not supported by 'strongest' evidence," clearly referring to the two types of GAO "strongest" evidence mentioned above. The fact that such evidence was lacking from the other 16% is self evident -- if it were not, then the GAO would not have differentiated the 16% and 9% groups.

50. George N. Lewis and Theodore A. Postol, "Video Evidence on the Effectiveness of Patriot during the 1991 Gulf War." *Science & Global Security* (1993): 4:56.

51. Single fixed values are presented both in Appendix B and on page 26. We use the range 3000 – 3500 psf for their characterization of the intact Scud because they present one number in the text and another in the Appendix.

52. Some may be tempted to compare the drag coefficient dependence modeled here with that of the V2 in Sutton, Rocket Propulsion Elements, p. 100. However, the V2 characteristics that are responsible for drag generation do not closely resemble those of the Scud. The V2 nose and afterbody sections are characterized by smooth contours of unusually high length-to-diameter ratio, together accounting for about two-thirds of the body length. Both of these act to substantially reduce drag compared to a Scud-like airframe that has a shorter conical nose and does not have a contoured afterbody. These differences alone preclude any inference of the Scud drag from that of the V2. Further, the ratio of the transonic peak drag coefficient to the zero-velocity drag coefficient is not generally meaningful since the physical mechanism of drag generation is completely different for these two flow regimes and will behave totally differently for different airframes.

53. We use 50 Km as a workable upper bound on break-up altitude. In terms of "time

to ground" from a representative range of intercept and video observation altitudes, the subject of interest in this discussion, the difference between a breakup altitude of 50 Km and a Scud warhead that separated even on ascent is insignificant.

54. This characterization by the panel of P&L's argument is found on page 19 of the Sullivan report. The only comment that the panel makes is in their note 43, where they state that they have no independent knowledge on this subject. Some independent knowledge, however, could have been obtained with some "back of the envelope" calculations on possible fragment strike angles and simple ray tracing of possible Scud paths within the Scud.

55. An "early bird" is an intercept in which the target and the interceptor are in the same plane and the point of closest approach occurs after the interceptor crosses the trajectory path of the target, i.e., the interceptor got there too early. A "late" bird is just the opposite and "right" and "left" birds represent similar conditions for out of plane but "on time" intercepts. In practice, most miss geometries are a combination of early/late and right/left. These specifics are important because they significantly influence the combination of warhead spray patterns, strike angles and fuzing performance. The impact of all of this is ignored by P&L and the panel.

56. The fact that the Desert Storm engagements took place in a closing velocity regime for which Patriot had not been designed, and that, in turn, the fuze was operating on the edge of its performance envelope, is not disputed. That has been reported repeatedly by a number of sources, including the US Army, and was part of the rationale for two different missile upgrades after the war. What we are arguing here is that P&L's characterization of armament system effectiveness at a "representative" end-game situation is misleading because of the high degree of non-linearity in this problem and because of the things they did not include in their analysis. These include crossing angle, angle of attack, a relatively wide range of both target and Patriot velocities, etc., all of which were present in the real world intercepts and all of which *fundamentally* change the relationship between the fuzing cone, the dynamic spray angle of the warhead, and their relationship to all of the velocity vectors that come into play when analyzing the combination of fuzing and warhead effectiveness. Of concern is not that P&L simplified their analyses, but that the panel failed to comment on the uncertainties that such simplification created.

57. 60% is the combined score of the publicly released figures of over 70% in Saudi Arabia and over 40% in Israel. This combined score was publicly referred to by then Secretary of Defense Cheney at the annual ADPA dinner in Washington DC on April 9, 1992 as well as at the House Government Operations Committee Congressional Hearing two days earlier. The panel states that they don't understand "what if anything the term 'over' is intended to convey in the reported success rates." We can at least eliminate their confusion here. The Army was attempting to make public unclassified suc-

cess rates based upon more precise classified numbers. They chose to round down to the nearest tenth percentile. Thus, "over 40%" means anywhere from 40% +ε to 50% - ε.

58. Charles A. Fowler wrote in "Defense Acquisition: Grab the Ax," "More than 4000 contractor personnel and many Government lab people were rushed to the Persian Gulf . . .. devising hardware and software fixes and improvements. . ." [Charles A. Fowler, "Defense Acquisition: Grab the Ax." *IEEE Spectrum*. (October, 1994): 57.]
Included in these 4000 contractor personnel were about 30 Raytheon missile engineers and logisticians who volunteered to place themselves in harm's way by going to the Gulf and help with training, logistics support and dealing with all of the threat unknowns and mission extensions that characterized the Patriot operation early in the war.